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14. ABSTRACT The objectives of the grant are to provide a systematic study to fill the gap between existing research on low Reynolds number turbulent flows to the kinds of turbulent flows encountered on full-scale vehicles. We are specifically interested in (1) the behavior of wakes at high Reynolds numbers with increasing complexity, varying from axisymmetric wakes, to wakes typical of submarine shapes that include the effects of a sail, fins, and control surfaces; and (2) the effects of roughness at high Reynolds numbers. We aim to gain a better understanding of complex flow interactions in wakes typical of submarine flow fields, especially wakes with concentrated regions of streamwise vorticity. We are also interested in high Reynolds number flows over rough surfaces, especially pipes and flat plates with roughness that relate to marine surfaces. We expect these studies to lead to improved flow prediction and improved flow control. The work is performed in two unique facilities: the Superpipe and the High Reynolds number Test Facility (HRTF) that can obtain very high Reynolds numbers on a laboratory scale using compressed air as the working fluid.					
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Final Technical Report

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Contract Information

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Technical Section

Technical Objectives

The objectives of the grant is to provide a systematic study to fill the gap between existing research on low Reynolds number turbulent flows to the kinds of turbulent flows encountered on full-scale vehicles. We are specifically interested in (1) the behavior of wakes at high Reynolds numbers with increasing complexity, varying from axisymmetric wakes, to wakes typical of submarine shapes that include the effects of a sail, fins, and control surfaces; and (2) the effects of roughness at high Reynolds numbers. We aim to gain a better understanding of complex flow interactions in wakes typical of submarine flow fields, especially wakes with concentrated regions of streamwise vorticity. We are also interested in high Reynolds number flows over rough surfaces, especially pipes and flat plates with roughness that relate to marine surfaces. We expect these studies to lead to improved flow prediction and improved flow control. The work is performed in two unique facilities: the Superpipe and the High Reynolds number Test Facility (HRTF) that can obtain very high Reynolds numbers on a laboratory scale using compressed air as the working fluid.

Technical Approach

Our studies are performed in two facilities constructed at Princeton under ONR funding. The Superpipe facility enables very accurate measurements in fully developed turbulent pipe flow across a wide range of Reynolds numbers, from 31×10^3 to 35×10^6 . High Reynolds numbers are achieved at a moderate cost by using compressed air at ambient temperatures as the working fluid, thereby decreasing the kinematic viscosity by over two orders of magnitude as compared to air at STP. The maximum static pressure is

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200 atm. The test pipe has a nominal diameter of 129 mm, and a length of 202 D. A diagram of the facility is shown in Figure 1.

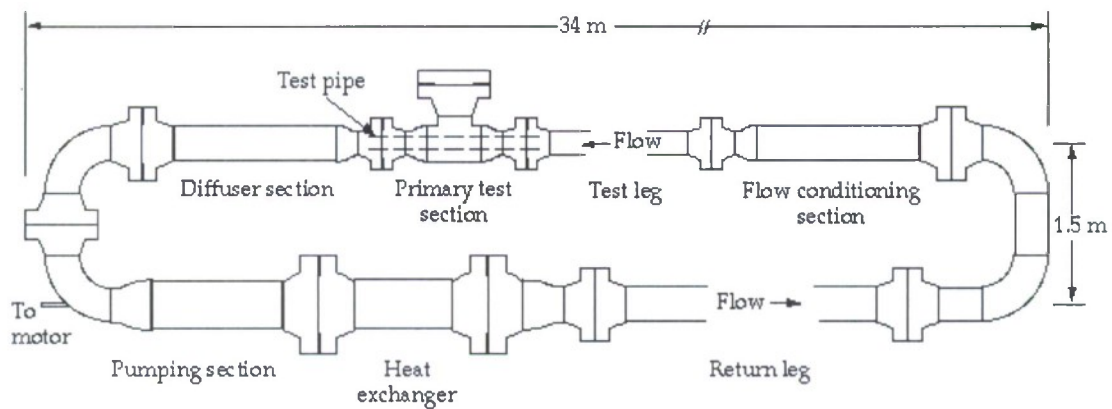


Figure 1: Princeton/DARPA/ONR Superpipe apparatus.

A wind tunnel to achieve high Reynolds numbers called the Princeton/ONR High Reynolds Number Testing Facility (HRTF) is also used to attain high Reynolds number. Like the Superpipe, it uses air at pressures up to 3,000psi as the working fluid (Figure 2). The primary purpose of the facility is to study the hydrodynamic forces, moments and flow-fields produced by submarine shapes up to length Reynolds numbers of 100×10^6 (approximately 1/10th full-scale). There are two working sections: each is 8ft long with an internal diameter of 18in. The facility will be equipped with a Magnetic Suspension Balance System (MSBS) to allow measurements free of the interference produced by the support systems usually employed in these applications. The MSBS was designed, constructed and tested under the supervision of Colin Britcher of ODU, and is expected to be delivered to Princeton in June , 2009.

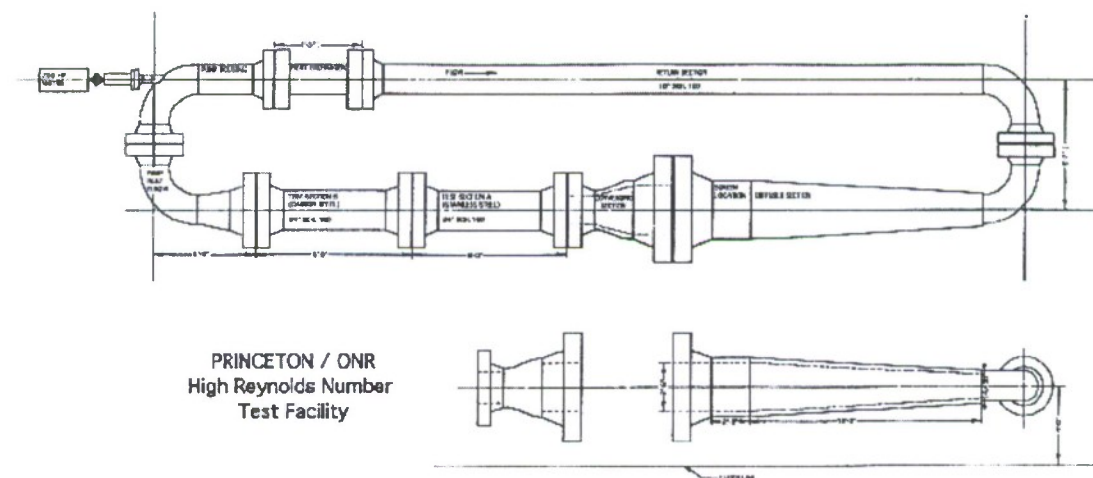


Figure 2: Princeton/ONR High Reynolds number Test Facility.

Progress

1. SUBOFF Wake Study:

We have studied the wake behind a SUBOFF model supported on an extension of the sail at locations $x/D = 3, 6, 9, 12, 15$ downstream of the stern at Reynolds numbers based on the model length of 1.1×10^6 , 12×10^6 , and 25×10^6 . Preliminary data have also been obtained at 45×10^6 and 75×10^6 . Mean flow and two-component turbulence data were obtained along a line aligned with the model support and located on the center of the wake.

The similarity variables for the far wake are u_0 and l_0 , which are the centerline velocity deficit and the half wake width (that is, the distance from the centerline to the point where the velocity deficit is half its maximum value), respectively. They are expected to scale with $a(x - x_0)^{-2/3}$ and $b(x - x_0)^{1/3}$. As shown in figure 3, the data support this scaling at all stations in the wake, with $x_0 = -2D$.

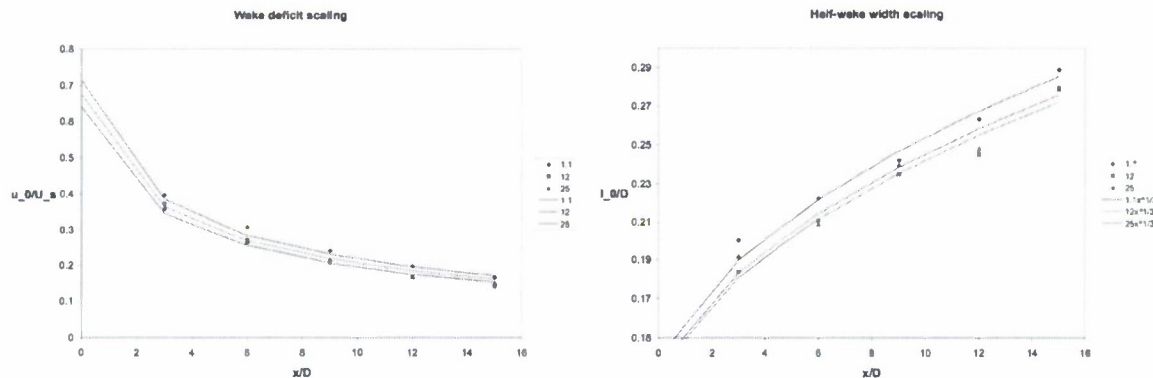


Figure 3: Similarity scaling of the velocity deficit (left) and the half-wake width (right).

It was shown that the mean flow velocity profiles (on the side opposite the support, where y is positive) attain similarity very quickly, and are well described by an exponential function. Results for the highest Reynolds number are shown in figure 2. The profiles are shown in similarity form using u_0 and l_0 . The mean velocity profiles on the support side (where y is negative) do not collapse with this scaling, which is unsurprising.

We have also shown that the turbulent stresses $\overline{u'^2}$, $\overline{v'^2}$, and $-\overline{u'v'}$ are still far from self-similar at a streamwise distance of $15D$ downstream of the stern. Results for streamwise component at the highest Reynolds number are shown in figure 4. The asymmetry in the profile due to the influence of the support is evident. Focusing on the side opposite from the support, there is some suggestion that the streamwise intensity may be approaching a self-similar state by $x/D = 15$, but the point at which the asymptotic behavior occurs is not known at this time. The overall behavior of $\overline{v'^2}$ is similar, although its magnitude is about 6 times smaller than $\overline{u'^2}$.

The data are somewhat similar to those obtained by Johansson & George (2006) for the wake of a circular disk, where the mean velocity attained self-similarity at $x/D = 10$ (the first station examined), and the streamwise turbulent intensities attained similarity at $x/D = 30$ (approximately).

The full data set is presented and discussed by Jiménez (2007), Jiménez & Smits (2009), and Jiménez et al. (2009).

The other important question is with regard to Reynolds number independence. The turbulence profiles obtained at the three lower Reynolds numbers (1.1×10^6 , 12×10^6 , and 25×10^6) showed that there was a rapid evolution between 1.1×10^6 and 12×10^6 , but the further evolution at 25×10^6 was relatively small. To check the behavior with increasing Reynolds number, preliminary data were obtained at 45×10^6 and 75×10^6 . These data strongly suggest that the turbulence profiles (scaled with similarity variables) become Reynolds number independent for Reynolds numbers greater or equal to 25×10^6 . This observation, if substantiated by our ongoing measurements, is a major result.

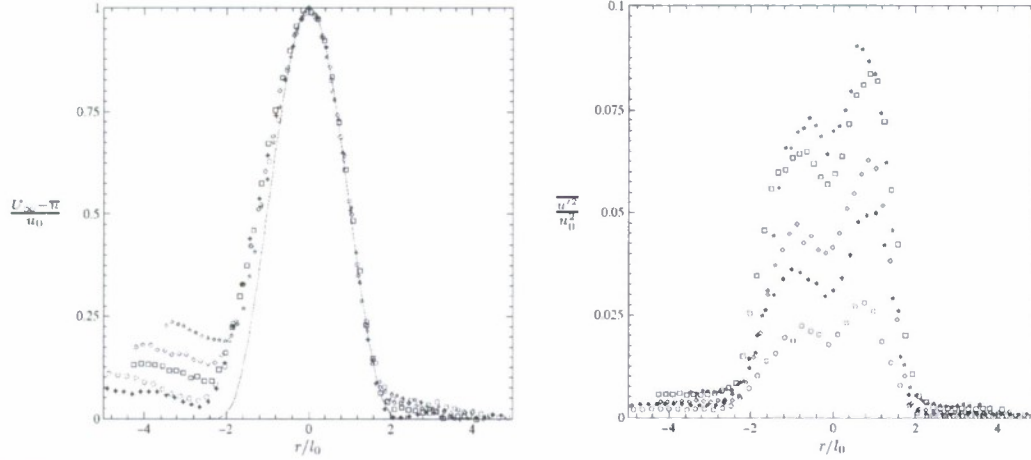


Figure 4: Mean velocity (left) and streamwise turbulence intensity (right) profiles in similarity form for $Re_L = 25 \times 10^6$.

One issue that is of particular concern is the accuracy of our hot wire measurements. In this respect, the primary issues are the temporal and spatial response of the probes. The pre-multiplied spectra on the centerline at the highest Reynolds number are shown in figure 5. The non-dimensional wavenumber $kl_0 = 2\pi fl_0/U$, where U is the local mean velocity and f is the frequency in Hz. In each case, the range of wavenumbers corresponding to the hot wire length l_w is shown as $2\pi l_0/l_w$. It appears that the spatial resolution of the probes is adequate to capture the energy in the signal at all positions and at all Reynolds numbers. In terms of temporal resolution, the maximum frequency content of the signal does not exceed about 2KHz, and since the hot wire signals were sampled at 10 KHz and low-pass filtered at 5 KHz, the temporal resolution of the probe is also adequate.

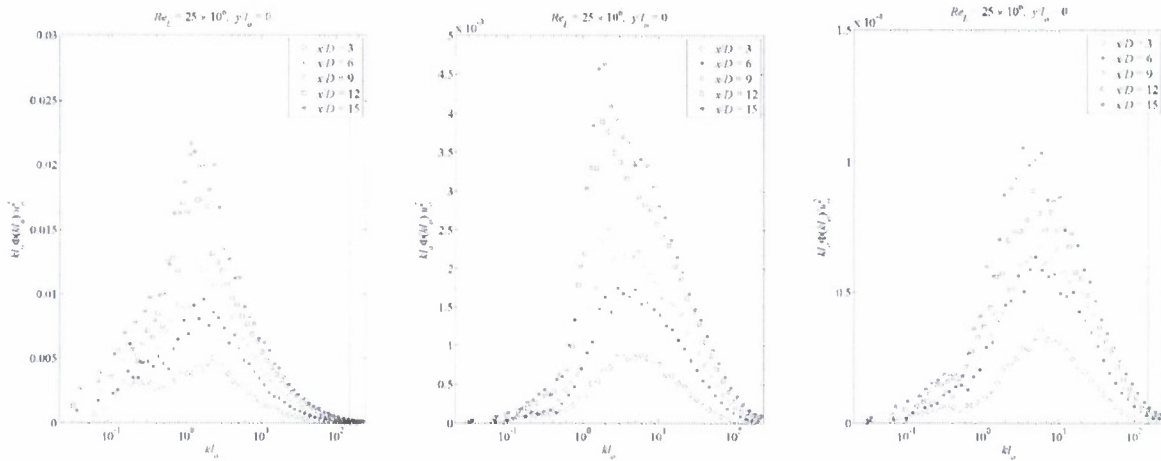


Figure 5: Pre-multiplied power spectral density of u' , v' , and $-u'v'$ in similarity form on the centerline at $Re_L = 25 \times 10^6$. The wavenumbers corresponding to the hot-wire length is shown as the vertical lines, with the solid line for $x/D = 3$, and the dashed line for $x/D = 15$.

The spectra reveal two peaks in the near-wake: one peak at a wavenumber of about 1 or 2, and another peak at a wavenumber of about 0.01 or 0.02. The lower wavenumber peak corresponds to a Strouhal number based on diameter and freestream velocity of about 0.22, suggesting that it is associated with an azimuthal or helical shedding mode in the wake structure. This mode is evident at all Reynolds numbers, at all cross-stream positions, indicating that it is unlikely to be due to the interference of the support wake with the model wake. The mode is seen only for $x/D < 15$, suggesting that it plays at least a partial role in the approach to self-similarity of the turbulent stresses.

2. Superpipe Studies

Two point hot-wire measurements of streamwise velocity were performed in the logarithmic and wake regions of turbulent pipe flow for Reynolds numbers, based on pipe diameter, ranging from 7.6×10^4 to 8.3×10^6 at four wall-normal positions with azimuthal probe separation. The azimuthal correlations were found to be consistent with the presence of very large-scale coherent regions of low-wavenumber, low-momentum fluid also observed in studies of wall-bounded flows. At the edge of the logarithmic layer the azimuthal scale determined from the correlations was found to be similar to that observed for channel flows but larger than observed for boundary layers, inconsistent with the concept of a universal logarithmic region (see figure 6). As the wall-normal position increased outside the logarithmic layer, there was a decrease in azimuthal scale relative to that of channel flow. Using cross-spectral analysis, high-wavenumber motion was found to grow azimuthally with wall-normal distance at a faster rate than the low-wavenumber motions. See Bailey et al. (2008) for further details.

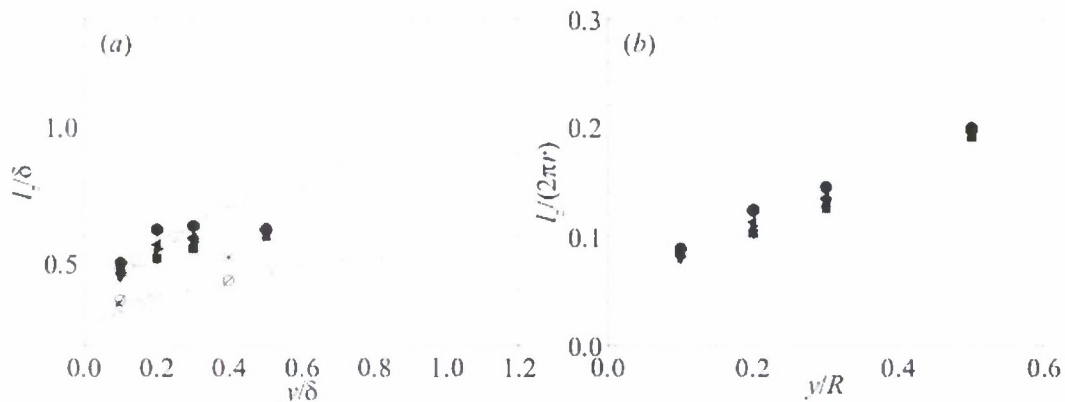


Figure 6: **Channel:** \square , Monty *et al.* (2007). **Channel DNS:** ∇ , Del Álamo *et al.* (2004). **Boundary layer:** \triangle , Tomkins & Adrian (2003); \triangleleft , Krogstad & Antonia (1994); \triangle , Hutchins *et al.* (2005); \diamond , Hutchins & Marusic (2007); \times Volino *et al.* (2007). **Rough-wall boundary layer:** \circ , Volino *et al.* (2007). **Pipe:** \circ , Monty *et al.* (2007); solid symbols: present results at different Re_D

3. Hot-wire Resolution and the Implementation of NSTAP

With respect to the hot wire measurements in the Superpipe, an important concern is the spatial response of the probes. This is particularly true for the near-wall measurements, but it may also be important in the outer region where we have shown the presence of an outer peak in the streamwise turbulence intensity (Morrison et al. 2003). The pre-multiplied spectra at three different wall distances at a Reynolds number

of 520×10^3 are shown in figure 7. The attenuation of the energy close to the wall due to the increased length of the hot wire is clearly evident.

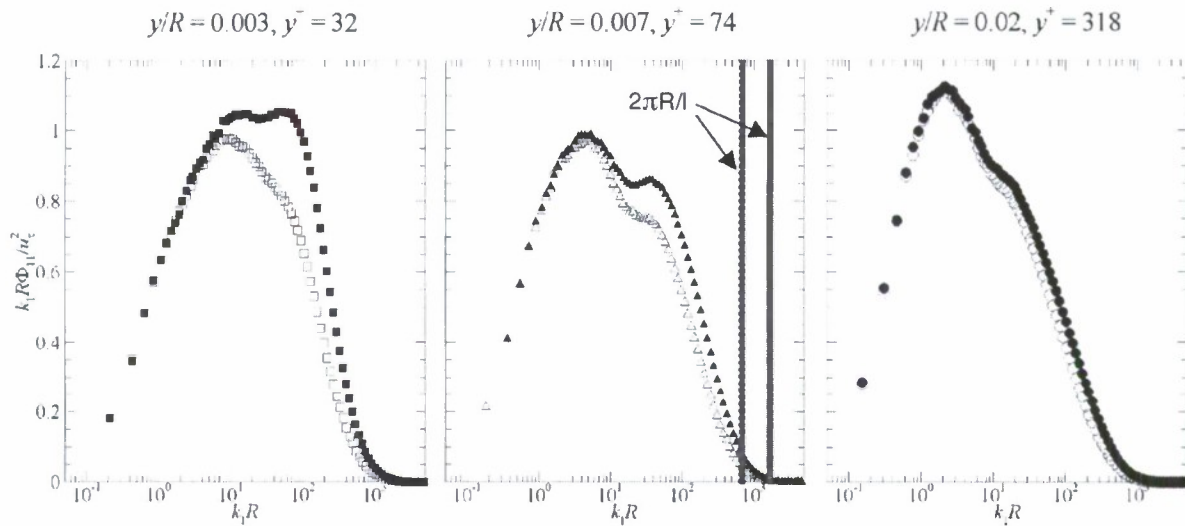


Figure 7: Pre-multiplied power spectral density of u' at $Re_D = 520 \times 10^3$ taken with two different wires. Filled symbols $l^+ = 58$, open symbols $l^+ = 100$. The wavenumbers corresponding to the hot-wire length is shown as the vertical lines.

With separate support from NSF, we have developed a new Nano-Scale Thermal Anemometry Probe (NSTAP), with a sensing wire over an order of magnitude smaller than current commercial hot-wires. It seems clear from results such as those shown in figure 5 (and much previous experience) that the probe length should always be less than about 20 viscous units. In preliminary tests of a 60 μm long NSTAP probe ($l/d \approx 300$) was tested in a constant temperature circuit and found to have a frequency response in excess of 200KHz. The spatial resolution of the NSTAP probe was demonstrated by measurements in the Superpipe at Reynolds numbers of 80,000 and 150,000 (figure 8). The mean velocity profiles agree well with the Pitot probe data of MeKeon et al. (2004), and the NSTAP provides new data very close to the wall (the minimum value of y^+ is about 2 and 4 for the two Reynolds numbers shown here). The streamwise turbulence intensity profiles demonstrate good agreement with the conventional hot wire data of Morrison et al. (2004). At these Reynolds numbers, the NSTAP length in terms of viscous units is about 1 and 2, respectively, allowing accurate measurements even deep within the viscous sublayer. Such measurements have never before been possible at these Reynolds numbers.

In the process of verifying the NSTAP data, highly accurate hot-wire data were obtained by paying special attention to calibration and issues of spatial resolution. The data, reported by Hultmark et al. (2009), are shown in figure 9 for Reynolds numbers up to 150×10^3 . The measurements indicate that the near-wall peak is invariant with Reynolds number in location and magnitude. The results agree with previous pipe flow data that have sufficient spatial resolution to avoid spatial filtering effects, but stand in contrast to similar results obtained in boundary layers, where the peak displays a strong Reynolds number dependence, although it is fixed at the same location as in pipe flow.

These results raise two interesting questions. The first is why there is an apparent discrepancy between the near wall scaling of pipe flows and boundary layers, where there has been reported a growth of the magnitude of the inner peak with increasing Reynolds number. It is clear that the outer layer structure of these flows are quite different (Bailey et al. 2008), so there could potentially be some difference in the interaction between the inner and outer layers between the two types of flows. The second interesting question is what will happen to the profiles of u'^2 at even larger Reynolds numbers. As shown in figure 9,

turbulence in the outer layer continues to grow with Reynolds number while the inner peak remains constant. Unless a high Reynolds number asymptote occurs due to the contribution to turbulent kinetic energy from the smallest turbulence scales becoming negligibly small, the magnitude of u'^2 in the outer layer will exceed that of the inner layer at some undetermined Reynolds number.

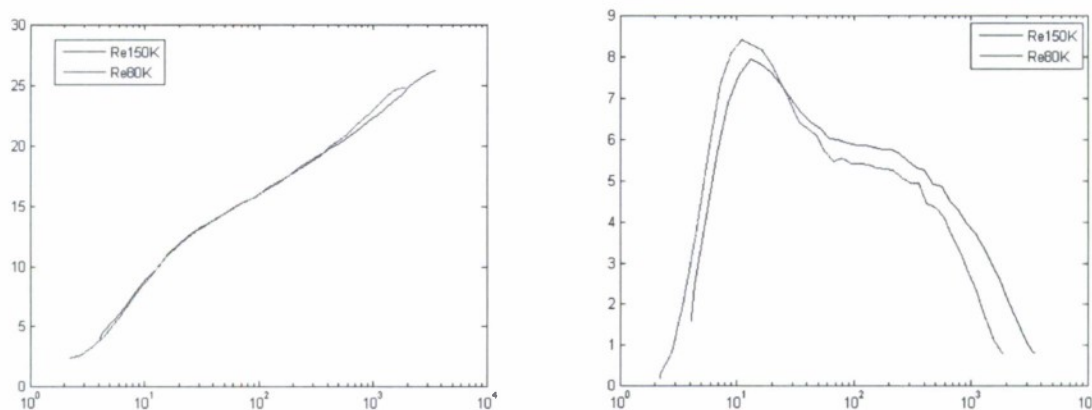


Figure 8: NSTAP measurements in fully developed pipe flow at $Re_D = 80 \times 10^3$, and 150×10^3 . Left: mean velocity profiles. Right: Turbulence intensity profiles.

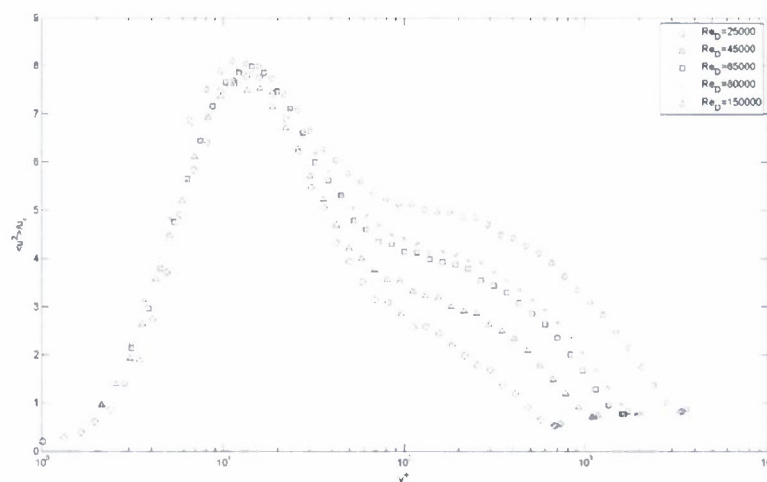


Figure 9: Hot-wire measurements in fully developed pipe flow at Re_D up to 150×10^3 .

4. Magnetic Suspension Balance System (MSBS)

The MSBS (figure 10) will be moved to Princeton in June 2009.

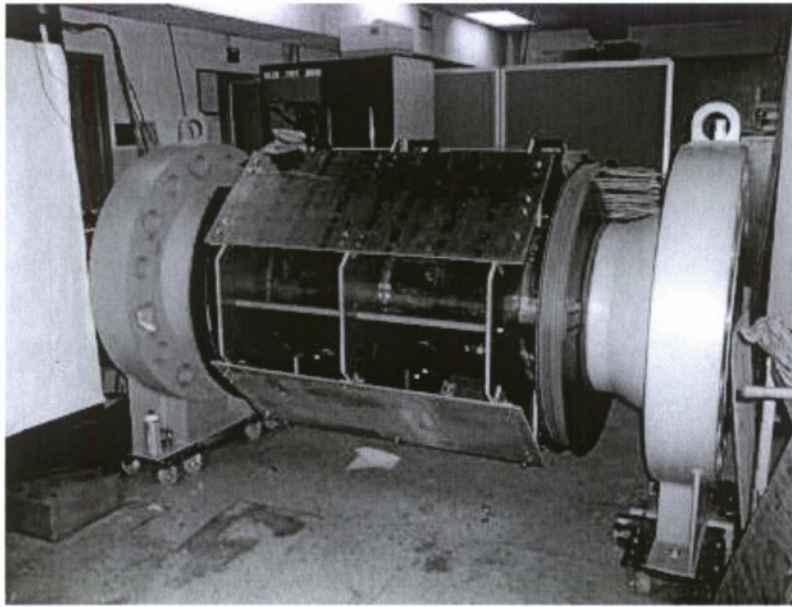


Figure 10: MSBS system on location at NASA LaRC. The system is expected to arrive at Princeton in June 2009.

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